

Modeling the Acoustic Channel for Simulation Studies

Dr. Michele Zorzi, PI
Department of Information Engineering, University of Padova
Via Gradenigo, 6/B – 35131 Padova, Italy
phone: +39-049-827-7762 fax: +39-049-827-7699 email: zorzi@dei.unipd.it

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<http://telecom.dei.unipd.it/pages/read/75/>

LONG-TERM GOALS

Underwater acoustic communications, especially from a single point-to-point link perspective, have been studied extensively in the past few decades. Underwater networking issues have begun to attract the interest of researchers as well, and represent a fertile research area which can be expected to grow in the future. Bringing the study of acoustic communications systems to the networking level has the potential to open up new directions and to provide a means to make them much more powerful and useful. Many military and naval applications can be expected to greatly benefit from this paradigm shift.

The main goal of the proposed work was to deepen our understanding of the behavior of the underwater acoustic channel and develop channel modeling techniques to enable more detailed studies at the networking level. To this aim, we started from existing data sets for point-to-point communications, in order to try and extract fundamental behaviors and model them in a way suitable for the simulation of more complex systems. This includes the integration of existing (as well as new) acoustic propagation modeling techniques into network simulators, the search for statistical models based on measured data, as well as the development of trace-based simulation techniques, and their validation and assessment in representative application scenarios.

OBJECTIVES

The project started on 04/01/10, and this final report covers the period from 09/01/11 to 09/30/12 (the last seven months of the second year, plus an additional six months granted as no-cost extension). The main objective for this period was to gain a deeper insight on the characteristics of the underwater acoustic channel that most affect the performance of communication systems and networking protocols. In order to do so, we made use of experimental data made available to us. Key channel quality features have been sought and quantified, including spatial correlations, and temporal variability over intervals of time pertaining not only to communication systems but also to networking protocols. Moreover, insights on how channel awareness can be exploited by communication systems and networks have been developed.

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APPROACH

The objective of the conducted research work is to develop simulation models able to correctly capture the behavior of acoustic propagation in underwater communication networks, while containing the proper level of detail that makes them realistic while still sufficiently lightweight for use in networking simulations.

The technical approach we proposed to adopt in the overall effort includes the following points: (i) deep interdisciplinary understanding of acoustic propagation environments and networking capabilities/requirements; (ii) identification and evaluation of the main PHY metrics that need to be used in networking studies; (iii) development of comprehensive simulation models that accurately reproduce the propagation characteristics of underwater channels, while also being suitable for use in networking studies; (iv) validation of the proposed models in the performance analysis of advanced communications and networking functionalities through detailed analysis, simulation, and experimentation.

In the reporting period (09/01/2011 through 09/30/2012), we focused on all points above. In particular, we (i) deepened our understanding of the underwater acoustic channel quality dynamics and its implications on protocol design; (ii) studied relevant PHY communications metrics according to the systems considered (including SNR, BER, channel impulse response, spatial correlation coefficients, amount of redundancy) as well as higher-layer metrics (including throughput, delay, and transmit energy consumption); (iii) evaluated the computational complexity of providing channel awareness in a network; (iv) applied the gained understanding to propose more reliable communication systems.

We highlight that the overall objectives are very ambitious and can be addressed from different (but complementary) points of view. The body of work we developed during the whole project can accordingly be categorized following several complementary approaches. An *inductive* approach was used in some of our studies, where we started from the data sets to extract information about the channel behavior, trying to highlight patterns (e.g., periodicity) and to verify some broad assumptions (e.g., stationarity). From the data we were able to infer some useful information about the channel behavior on different time scales, which then allowed us to make some modeling assumptions based on experimental evidence. A complementary *deductive* approach was instead used when a model was assumed in order to assess the performance of networking schemes or to derive general methods able to improve the reliability of underwater acoustic communications. Finally, we also adopted a *simulation based* approach, where experimental evidence is replaced by simulated data, which is easier, faster, and cheaper to obtain and makes it possible to study scenarios that are too difficult to experiment with.

The project team for the reporting period includes Prof. Michele Zorzi (PI), Prof. Gianfranco Pierobon (co-PI), Dr. Paolo Casari (post-doctoral researchers) and Dr. Beatrice Tomasi (PhD student until 12/31/2011 and then post-doctoral researcher), Mr. Daniele Munaretto (PhD student), Mr. Giovanni Toso (engineer) and Mr. Matteo Lazzarin (MS student).

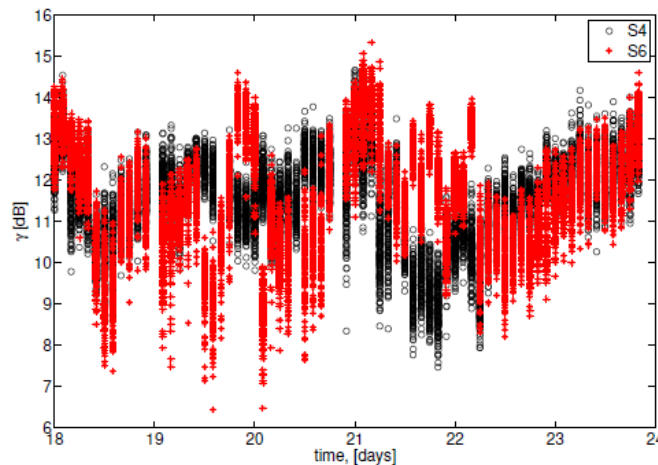
WORK COMPLETED AND RESULTS

The focus of the work in the final part of the project has been the following: (i) identification of important channel features affecting the performance of communications systems and networking protocols; (ii) evaluation of the feasibility of channel aware communications and networking solutions;

(iii) investigation of solutions for more reliable underwater acoustic communications; and (iv) simplified analytical investigations of networking schemes and their validation.

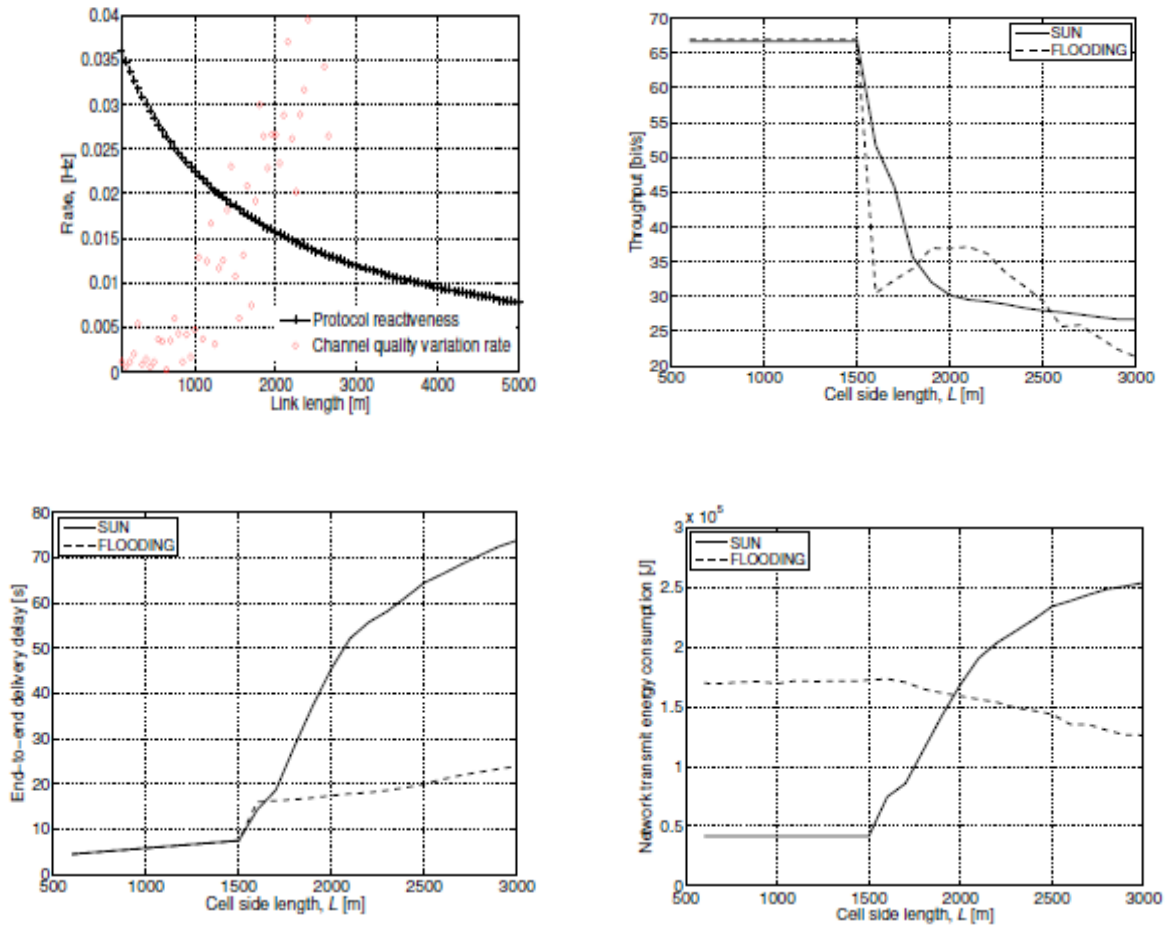
As during the previous reporting period, we based our studies on the analysis of three data sets, namely SPACE08 (performed in October 2008 at the Martha's Vineyard Coastal Observatory operated by the Woods Hole Oceanographic Institution), SUBNET09 (performed in Summer 2009 at the Pianosa Island in the Tyrrhenian Sea, Italy, by the NATO Undersea Research Centre) and KAM11 (performed in June and July 2011 off the coast of the Kauai island, Hawaii, by a consortium of academic institutions under MURI support). Descriptions of these data sets can be found in previous reports.

As to point (i), *identification of important channel features affecting the performance of communications systems and networking protocols*, we have investigated the spatial relationship among simultaneous channel quality metrics collected during SPACE08. The main results suggest that receivers at a distance of 200 m and 1000 m from the transmitter could experience comparable communication performance. In particular, we evaluated the communication channel quality, on which performance depends, in terms of output SNR (after equalization). This counter-intuitive result is justified by observing the channel conditions at the different ranges. For closer receivers, the channel exhibits a longer delay spread of the channel impulse response, along with faster time-varying delayed arrivals. Such fast varying late arrivals, which are affected by the bounces off the surface, make it difficult for the DFE to keep track of their fluctuations, thus causing time-varying ISI. On the other hand, the channel observed at farther positions exhibits a less spread channel impulse response, along with more stable conditions. However, the signal reaches the receivers with larger attenuation, thus giving rise to comparable communication performance. Even though distance is an important parameter when computing the transmission loss, and therefore in assessing the communication performance of non-coherent communication systems, this may not hold also for coherent receivers. This evaluation and comparison between communication performance at different ranges is a starting point toward more general problems, such as whether or not distance (operating frequency is not considered since it is given as a system parameter) plays the main role when determining the performance of coherent receiving systems in shallow waters. Results would suggest a negative answer, thus raising the question of which other parameters should be taken into account, when in a simulator we want to replicate the statistics (both spatial and temporal) of communications performance for coherent receiving systems in shallow water. The figure below represents the time series of the estimated output SNR at systems S4 and S6, which were at a distance of 200 and 1000 m from the transmitter, respectively.



These results have been published and discussed in [OCEANS12], where various additional results, as well as a thorough analytical development, are also reported.

Another study on the channel characteristics that affect the performance of communications and networking can be found in [UCOMMS12]. These results are useful to better understand what channel conditions should be modeled in a network simulator, in order to get representative performance evaluations, when non-coherent receivers are employed. In particular, this work aims at evaluating how the time variability of the channel conditions and of the communication performance impacts the performance of routing protocols. In order to do so, we compute the performance of a reactive routing protocol when time-varying channel conditions were reproduced at varying distances among relay nodes. The obtained performance as a function of the distance between two relay nodes is also compared with that of a flooding routing algorithm, which does not rely on any best path establishment procedure and therefore is not affected by time-varying channel conditions. Results confirm that the performance of a reactive protocol decreases after a critical distance between two relay nodes. Such critical distance depends on both the response time of the protocol and the maximum rate of the time-varying channel conditions along the chosen best path. The figures below represent the performance in terms of throughput, end-to-end delays and transmit energy consumption as a function of the network density (or single-hop link length). The first figure on the left shows the relationship between the protocol reactivity and the channel fluctuation rate as a function of the link length, whereas the other three figures show a performance comparison between our reactive protocol and simple flooding.

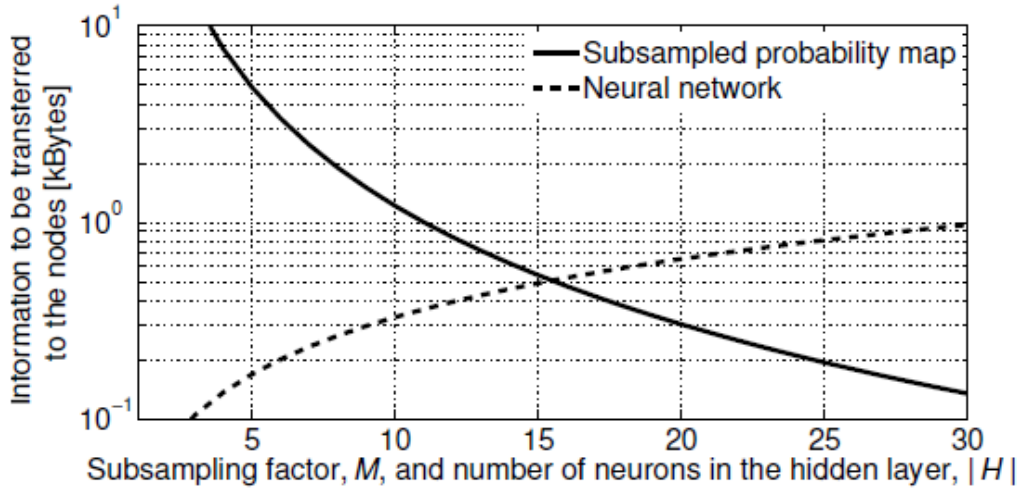


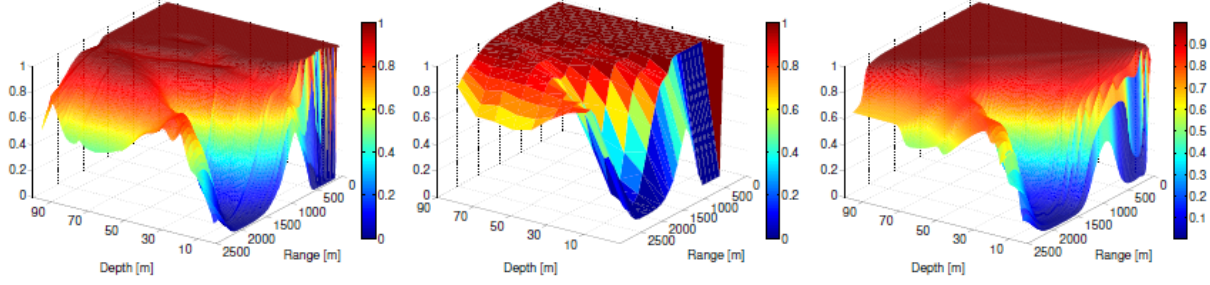
On the one hand, these results suggest that time variability (or representative statistics) should be modeled in a network simulator, in order to evaluate and compare the performance of networking protocols. On the other hand, the gained insights make it possible to design networking protocols that are more suitable for underwater acoustic networks according to the actual conditions.

Various additional results, as well as a thorough description of the schemes considered, can be found in [UCOMMS12].

As to point (ii), *evaluation of the feasibility of channel aware communication and networking solutions*, we have focused on the problem of transferring channel state information (CSI) to the nodes of an underwater network.

As the CSI is derived by simulating the behavior of the underwater channel via ray tracing, we first discussed a parallel implementation of the ray tracing software obtained using the CUDA architecture, that helps to compute the CSI faster. We then considered the problem of making the channel state information compact, and suitable for transmission over underwater acoustic channels. Results indicated that a Feedforward Artificial Neural Network (FANN) achieves both good accuracy and good compression of the CSI. The figure below shows the amount of information (in kBytes) to be transferred to the network nodes in order to make them channel-aware. The abscissa represents the subsampling factor in case a subsampled probability map is transmitted, or the number of neurons in the hidden FANN layer in case the weights of the FANN are transmitted. In the following figure, we show the original map (a), and compare it to the approximate maps that result from subsampling by a factor $M = 8$ (b), and from training a FANN with $H = 30$ hidden neurons (c). For these values the cases (b) and (c) achieve approximately the same map size of 1 kByte. We observe that the FANN approximates better the ridges and troughs of the map with respect to plain subsampling.



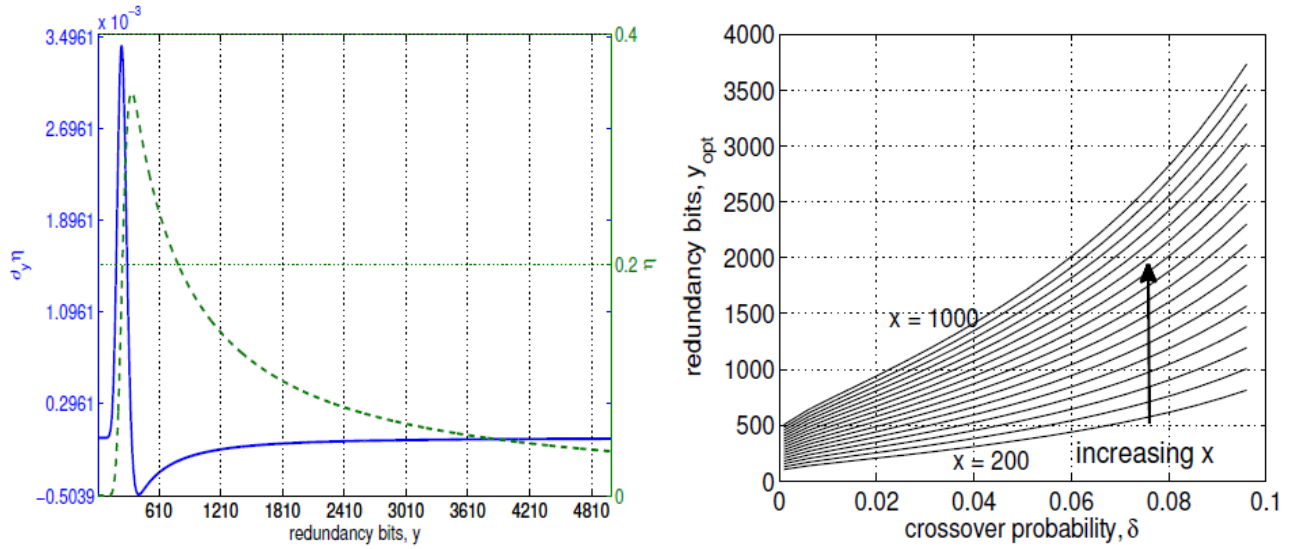


Based on these results, we can say that having fast tools for computing the CSI would enable channel awareness at the nodes of an underwater network, provided that the CSI can be suitably compressed. To this end, we showed that neural networks represent a suitable tool to accurately approximate the CSI, while keeping the amount of information to be transferred to the underwater network limited.

Various additional results, as well as a thorough discussion of the various aspects, can be found in [ECUA12].

As to point (iii) *investigation of solutions for more reliable underwater acoustic communications*, we have leveraged on the gained insights on the underwater acoustic channel, in order to investigate and propose solutions to the reliability problem. In particular, we jointly addressed reliability and energy-efficiency in underwater acoustic communications by proposing online redundancy allocation over time-varying conditions in a communication link.

In particular, we built an optimization framework, based on a BSC channel model. Such model is proved to reflect in a simple way but without loss of generality the channel conditions measured during short intervals of time. Such channel model is valid on a time scale over which the bit error probability does not vary. We defined a metric representing how efficiently the information is encoded in terms of both spectral efficiency and energy consumption and we formulated the optimization problem to maximize such metric. Finally, we designed a real-time algorithm to compute the redundancy required in a UWA communication link. The presented study and results pave the way for future work. In particular, we plan to evaluate the efficiency of the proposed algorithm as a function of average SINR and channel coherence time. Moreover, we want to investigate how to allocate in real time the redundancy over longer packets, for which Markov channel models should be validated. As a final goal, we want to understand whether short or long packets are more efficient (in terms of both bandwidth and energy) in UWA communication systems. As an example of the obtained results, in the figure on the left below, we show the considered metric for optimization and its first derivative with respect to y (the number of redundant bits), when x (the number of information bits) is 200 and the channel error probability is 0.046. In the figure on the right, the y -axis represents the optimal number of redundancy bits, obtained from the optimization framework, for varying x (represented by the different curves) as a function of the crossover probability.



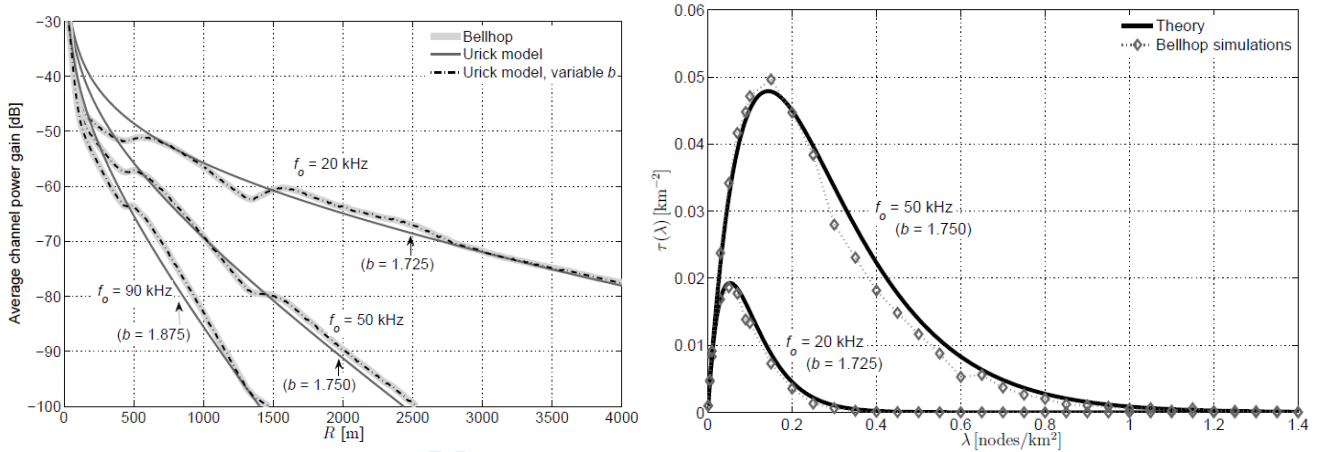
This study is an example of how studies on channel models would spur the development of more efficient underwater acoustic communication systems.

Various additional results, as well as a thorough analytical development, can be found in [WUWNET12].

Finally, as to point (iv) *simplified analytical investigations of networking schemes and their validation* we developed an analytical stochastic geometry approach for throughput evaluation in a random access underwater network, and developed a novel approach for its validation using simulation.

More specifically, we proposed a theoretical framework to evaluate the expected throughput of underwater networks over an ensemble of node topologies and propagation environments. The analysis is based on the assumptions that the transmitters are spatially distributed according to a Poisson point process, and that the channel follows a Rayleigh fading distribution, with a mean that is determined by spreading loss and frequency-dependent absorption. We evaluated the probability of a successful transmission, i.e., the probability that the signal-to-interference-and-noise ratio at the typical receiver is greater than a given threshold, and determine the maximum network throughput density over the transmitter density and the operating frequency.

The part of this work that is most relevant to the current project is the validation of the theoretical results using a realistic underwater channel simulator based on ray tracing. We proposed a novel validation approach, which enabled us to demonstrate that, for a number of practical scenarios, the theoretical and simulated throughput match provided that the spreading-loss exponent is appropriately fitted to the simulation scenario. An example of the results obtained is provided below. The figure on the left shows the average channel power gain as a function of the transmitter-receiver distance obtained through Bellhop simulation, and its fit using Urick's empirical formulas, whereas the figure on the right shows the match between the analytical throughput results obtained from our theoretical approach using the fitted Urick's model and the corresponding simulation results obtained using Bellhop to characterize the channel behavior. The match of the results obtained through the two approaches is quite remarkable, and shows that this analysis is very accurate.



Overall, the proposed framework provides easy-to-obtain network throughput results, which can be used as a complement or alternative to time-costly, deployment-dependent network simulations. Note in fact that the type of result shown above would be impossible to obtain experimentally, and very difficult even by simulation, since it involves averaging over a large number of independent topologies. Further considerations, as well as more results and the full details of the analytical approach, are reported in [TWC2012].

DISSEMINATION ACTIVITIES

The results obtained in the conducted research have been disseminated to the research community. Besides publishing and presenting the various contributions in relevant conferences and journals, special attention has been given to keynote and invited talks at international conferences, research centers and universities. In particular the PI gave two keynote speeches at IEEE IWCNC and UCOMMS, held in Lymassol, Cyprus, in Aug. 2012 and in Sestri Levante, Italy, in Sep. 2012, respectively. Moreover, Dr. Paolo Casari presented relevant results in an invited talk at CTTC in Barcelona, Spain, and Dr. Beatrice Tomasi was invited to present these results at the University of Aalborg, Denmark. Moreover, in order to make available the results of the post-processing done on the data sets, we implemented a website where such processed data can be downloaded through a controlled login/password procedure. Acknowledgements to the institutions and personnel as well as to ONR will be given in the webpage.

The PI and Drs. Casari and Tomasi took part in the UCOMMS conference in Sestri Levante, Italy, Sep. 12-14. 2012, whose topic was essentially the same as that of this project. This event was an excellent venue for dissemination of our own results as well as for discussion with interested researchers. The PI and Dr. Casari were also invited to participate in the subsequent UCOMMS workshop (Sep. 17-18, 2012), with the objective to provide concrete recommendations and best practices towards effective modeling of channel behaviors for communication and networking studies. The results and insights drawn from this project proved extremely valuable and relevant in that discussion. The keynote given by the PI [UCOMMS12_KEYNOTE] provided a useful research agenda for upcoming efforts in this area.

IMPACT/APPLICATIONS

Many of the behaviors revealed by our analysis, as well as some of the schemes proposed, are novel, and are expected to shed some light on how propagation affects the performance of underwater communication systems. We expect that these results will provide an interesting starting point to other researchers and will stimulate additional creative work.

In particular, the results presented in this report disclose future promising developments for both underwater acoustic communication systems and networks. In fact, the work on spatial correlation raises the question on whether or not an optimal communication region, included between a minimum and maximum distance, exists. The work on the computational complexity of making nodes in a network channel aware suggests that channel aware networking solutions may be feasible. The work on the impact of distance and time-variability of channel qualities on a reactive routing protocol suggests that some key channel characteristics should be taken into account when designing ad hoc solutions for underwater acoustic communication networks. The results on online redundancy allocation provide a starting point for the development of more reliable communications in the time-varying underwater acoustic channel conditions. Finally, the analytical approach for the throughput computation in random underwater networks shows the potential of theoretical developments and provides a novel validation approach that can be reused in different contexts.

We believe that the insights drawn from the research performed during this project are very valuable and useful to improve our understanding of the behavior of the acoustic channel and its effect on communication systems and networks. The results obtained clearly show that there are gains to be obtained when trying to connect the channel behavior to communications and networking studies and design. The presented results are only the starting point, scratching the surface of what promises to be a fertile research area for years to come.

RELATED PROJECTS

During the reporting period, the PI has been involved in an NSF project at UC San Diego (CNS-1035828 CPS: Medium: Collaborative Research: Networked Sensor Swarm of Underwater Drifters), an interdisciplinary effort including localization, networking, and ocean science. While there is essentially no overlap with the current project, it is possible that as part of that effort we will be able to perform some ad hoc channel measurements that will provide some additional data for our analysis. The PI has also had some related efforts funded by the European Commission and by an Italian foundation. The focus of such efforts is more on protocol design than on channel modeling and therefore those projects are complementary and non-overlapping with respect to the present one.

PUBLICATIONS

During the reporting period, several papers have been published and/or accepted, all carrying the acknowledgement to ONR funding. The following conference papers include technical achievements of the project and have been referenced in this report (journal versions are currently in preparation):

[OCEANS12] Beatrice Tomasi, James Preisig, Michele Zorzi, "On the spatial correlation in shallow water and its impact on networking protocols," in Proc. of IEEE Oceans 2012, Yeosu, South Korea, May 2012.

[UCOMMS12] Beatrice Tomasi, Giovanni Toso, Paolo Casari, Michele Zorzi, "On the impact of time-varying acoustic channels on routing protocols for underwater networks " in Proc. of UCOMMS, Sestri Levante, Italy, Sept. 2012.

[WUWNET12] Beatrice Tomasi, Daniele Munaretto, James C. Preisig, Michele Zorzi, " Realtime redundancy allocation for time-varying underwater acoustic channels," accepted for presentation at ACM WUWNet, Los Angeles, USA, Nov. 2012.

[ECUA12] Matteo Lazzarin, Paolo Casari, Michele Zorzi, "Endowing Underwater Networks with Channel Awareness: a discussion on computational complexity and information size issues," in Proc. of ECUA, Edinburg, UK, June 2012 .

[UCOMMS12_KEYNOTE] Michele Zorzi, "Modeling the UnderWater Acoustic (UWA) channel for simulation studies," keynote presentation at UComms, Sestri Levante, Italy, Sept. 2012.

The following journal paper, which was mentioned also in the previous report, has been published during the current reporting period:

[ROYAL12] John Heidemann, Milica Stojanovic, Michele Zorzi, "Underwater Sensor Networks: Applications, Advances, and Challenges," *Phil. Trans. R. Soc. A*, vol. **370**, pp. 158-175, 2012.

Finally, the following journal paper is currently under review:

[TWC12] Kostas Stamatiou, Paolo Casari, Michele Zorzi, "The Throughput of Underwater Networks: Analysis and Validation using a Ray Tracing Simulator," submitted to the *IEEE Trans. on Wireless Communications*, Feb. 2012, revised Jun. 2012.

Copies of these papers can be downloaded from www.dei.unipd.it/~zorzi/ONR2012

HONORS/AWARDS/PRIZES

Michele Zorzi:

- IEEE Fellow, 2007
- Member-at-Large of the IEEE Communications Society Board of Governors, 2009-2011
- Editor-in-Chief of the IEEE Transactions on Communications, 2008-2011
- Editor-in-Chief of the IEEE Wireless Communications magazine, 2003-2005
- Editor for Europe of the Wiley Journal on Wireless Communications and Mobile Computing
- Keynote Speaker, European Wireless conference, Lucca, Italy, Apr. 2010. (Address was on protocol design issues and channel modelling in underwater acoustic networks.)
- Keynote Speaker, Wireless Days conference, Venice, Italy, Oct. 2010. (Address was on protocol design issues and channel modelling in underwater acoustic networks.)
- Keynote Speaker, IWCMC, Lymassol, Cyprus, Aug. 2012. (Address was on protocol design issues and channel modelling in underwater acoustic networks.)

- Keynote Speaker, UCOMMS conference, Sestri Levante, Italy, Sep. 2012. (Address was on channel modelling in underwater acoustic networks.)
- Best Paper Award, IEEE MobiWac Workshop, June 2005
- Best Paper Award, IEEE CAMAD, June 2006
- Best Paper Award, IEEE GLOBECOM (Wireless Networks Symposium), November 2007
- Best Tutorial Paper Award, IEEE Communications Society, 2007
- Best Paper Award, European Wireless Conference, May 2009
- Guest Editor of several special issues, and in particular: “Underwater Acoustic Communications and Networks,” *IEEE Journal on Selected Areas in Communications*, December 2008

Member of the organizing and technical program committees of many conferences, and in particular: Technical Program co-Chair, ACM WUWNet’07